U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-255 094

EVALUATION OF MAGNETICS FOR FINE PARTICLE CONTROL

MIDWEST RESEARCH INSTITUTE

PREPARED FOR
INDUSTRIAL ENVIRONMENTAL RESEARCH
LABORATORY

MAY 1976

208021

EPA-600/2-76-133
May 1976

PB 255 094

Environmental Protection Technology Series

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-76-133	2.
3. RECIPIENT'S ACCESSION NO. PB255094	
4. TITLE AND SUBTITLE: Evaluation of Magnetics for Fine Particle Control	5. REPORT DATE: May 1976
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): K. P. Ananth and L. J. Shannon	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110	10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADL-029
	11. CONTRACT/GRANT NO. 68-02-1324, Task 26
12. SPONSORING AGENCY NAME AND ADDRESS: EPA, Office of Research and Development, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED: Task Final; 2/75-2/76
	14. SPONSORING AGENCY CODE: EPA-ORD

15. SUPPLEMENTARY NOTES: Task officer for this report is D. C. Drehmel, Mail Drop 61, Ext 2925.

16. ABSTRACT

The report gives results of an evaluation of the effectiveness of magnetic agglomeration/separation techniques in enhancing fine particulate capture. Whereas residence times and magnetic fields required to achieve agglomeration via magnetic forces appear to be unrealistic, magnetic separation--especially high gradient magnetic separation--appears to be attractive in principle.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Magnetic Properties	Stationary Sources	20C
Agglomeration	Fine Particulate	
Separation		
Dust		11G

18. DISTRIBUTION STATEMENT: Unlimited	19. SECURITY CLASS (This Report): Unclassified	21. NO. OF PAGES: 34
	20 SECURITY CLASS (This page): Unclassified	22. PRICE: 4.00

EPA Form 2220-1 (9-73)

EPA-600/2-76-133
May 1976

EVALUATION OF MAGNETICS FOR FINE PARTICLE CONTROL

by

K. P. Ananth and L. J. Shannon

Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

Contract No. 68-02-1324, Task 26
ROAP No. 21ADL-029
Program Element No. 1AB012

EPA Task Officer: Dennis C. Drehmel

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

CONTENTS

		Page
List of Figures		iv
List of Tables		v
Acknowledgments		vi
Summary		1
Sections		
I	Introduction	3
II	Particle Agglomeration in Magnetic Fields	4
	Magnetic Fields and Charged Particles	4
	Magnetic Fields and Uncharged Particles	11
III	Magnetic Separation	16
	Operation of a HGMS	16
	Principle of a HGMS	18
	Laboratory Study of HGMS	24
	Comparison of Magnetic Force With Conventional Mechanisms	24
IV	Conclusions	26
References		27

FIGURES

No.		Page
1	The Magnetic Force F Acting on a Charged Particle. . . .	5
2	Arrangement to Generate a Strongly Nonhomogeneous Magnetic Field H, Which Can Be Used to Separate Ferromagnetic Particles.	15
3	Schematic Representation of Helm Type High Gradient Magnetic Separator	17
4	Cross Section of Spherical Particle, Radius r_p Attached to Ferromagnetic Wire, Radius a, Magnetized by Uniform Magnetic Field H_o.	19
5	Log-Log Plot of Magnetic (F_m) and Competing Gravitational (F_g) and Drag Forces (F_d) Versus Particle Size r_p for Magnetized Wire Whose Size is Matched to That of Particle to be Trapped. Computed for CuO Particle Attracted by Ferromagnetic Wire of Radius $3r_p$ Magnetized by 10 KOe Field Strength and Acted Upon by Slurry With Velocity of 5 cm/sec.	21
6	Log-Log Plot of Magnetization Versus Particle Radii. . . .	23

TABLES

No.		Page
1	Terminal Drift Velocity of Particles in a Magnetic Field . .	7
2	Maximum Particle Charge as a Function of Particle Size . . .	10

ACKNOWLEDGMENTS

The work presented in this report was performed by Midwest Research Institute for the Industrial Environmental Research Laboratory-RTP of the Environmental Protection Agency as Task Order No. 26 of Contract No. 68-02-1324. The work was performed by Dr. K. P. Ananth, Senior Environmental Engineer, and Dr. L. J. Shannon, Assistant Director, Physical Sciences Division. The authors appreciate the helpful comments provided by Dr. Dennis Drehmel, the EPA Project Officer, in conducting this study.

SUMMARY

Increasing concern for better control of fine particulates has directed efforts toward development of new systems that are inherently more effective than conventional control devices or seeking systems that can improve the effectiveness of existing conventional devices in capturing fine particulates. This evaluation was undertaken to determine the effect of using magnetic forces to: (a) agglomerate fine particulates and assist their capture in conventional control devices; and (b) directly capture fine particulates in magnetic devices.

The use of magnetic fields to agglomerate either charged or uncharged particles is of no apparent utility in industrial gas cleaning applications. In the case of charged particles, residence times clearly in excess of those tolerable in industrial situations would be required to achieve any appreciable agglomeration.

Dipole forces, created by external magnetic fields, can influence the agglomeration of uncharged particles. However, significant enhancement of agglomeration rates occurs only for ferromagnetic materials in the presence of very strong magnetic fields. Since the particulate pollutants emitted from most industrial sources are not ferromagnetic, the use of dipole forces caused by magnetic fields is of no real significance. Also, it is quite likely that, even with ferromagnetic materials, unacceptable residence times would be required to effectively utilize dipole forces.

Direct capture of fine particulates should be readily achievable, in principle, in magnetic separators provided the particles are ferromagnetic in nature and the magnetic force acting on them is greater than the competing forces of gravitation and hydrodynamic drag. However, as noted previously, many particulates of interest are only weakly ferromagnetic or paramagnetic in nature and high magnetic field gradients are needed to achieve particle capture. Another potential problem could involve producing the high gradients and large magnetic forces over a surface area large enough to trap practical numbers of particles.

Currently, high magnetic field gradients have been generated by applying a relatively uniform background magnetic field to a ferromagnetic structure (grids, screens, steel wool, etc.) and inducing magnetic poles along properly oriented edges. A device using this approach is the high gradient magnetic separator (HGMS) which has been successfully used in mineral beneficiation and wastewater treatment. Despite the fact that this device has not apparently been used for particulate collection in industrial gas cleaning systems, it is attractive in principle, and warrants further investigation.

SECTION I

INTRODUCTION

The search for new systems to enhance fine particulate control has directed efforts toward evaluating the agglomeration of fine particulates by magnetic forces and toward evaluating magnetic devices for direct capture of fine particulates. If magnetic forces are effective in agglomerating fine particulates, then the agglomerates can be easily handled by conventional control devices.

Agglomeration of particles is a complicated process. A variety of forces causing the movement of particles toward one another may interact to produce collisions and subsequent agglomeration. As the particles collide and agglomerate, the concentration of each size changes with time, each size interacts with every other size, and the agglomeration rates change with size and concentration. Individual mechanisms of particle agglomeration will be more effective under certain conditions and the optimum utilization of one or more mechanisms will require well designed systems.

Agglomeration of particles by magnetic forces is occasionally mentioned in the literature, but little effort has been devoted to either theoretical or experimental studies of the process. Magnetic fields can alter the motion of particles suspended in a gas stream depending upon the magnetic permeability of the particles and magnetic fields might be used to enhance the agglomeration of both charged and uncharged particles. Particle agglomeration via the interaction of magnetic fields with charged particles is reviewed in the next section. This discussion is followed by discussions of magnetic fields and uncharged particles and magnetic separation, primarily the high gradient magnetic separation technique (HGMS). A brief conclusion is also presented.

SECTION II

PARTICLE AGGLOMERATION IN MAGNETIC FIELDS

Mechanisms by which particles may agglomerate in magnetic fields are reviewed in this section. The interactions of electrically charged particles with no intrinsic magnetic properties are discussed first followed by a review of the influence of permanent and induced dipole moments on agglomeration.

MAGNETIC FIELDS AND CHARGED PARTICLES

When an electrically charged particle with no intrinsic magnetic properties moves in a magnetic field transverse to the field lines, a force is generated on the particle. The resulting force is termed the Lorentz force. If a particle carrying N elementary charges "e" moves with a velocity v_p, the direction of the resulting force will be at right angles to both the direction of the field and the direction of motion of the particle (see Figure 1). As a result of the Lorentz force, the particle will be diverted from its original path. The magnitude of this force is found to be directly proportional to the velocity. If the velocity v_p of the moving charged particle is not perpendicular to the direction of the magnetic field, but makes an angle $\emptyset$ with the field, then the velocity vector v_p may be resolved into two components: $v_p \cos \emptyset$ in the direction of the field, and $v_p \sin \emptyset$ perpendicular to the field. In this general case, the force acting on the moving charged particle is perpendicular to both the magnetic field and to $v_p \sin \emptyset$, and has a magnitude proportional to $v_p \sin \emptyset$, as shown in Figure 1.

The potential for collisions and possible agglomeration of particles can be qualitatively assessed by determining the terminal drift velocity of a particle in a magnetic field. The terminal drift velocity can be obtained by equating the Lorentz force to the resistance of the gas, calculated from the Stokes-Cunningham Law:

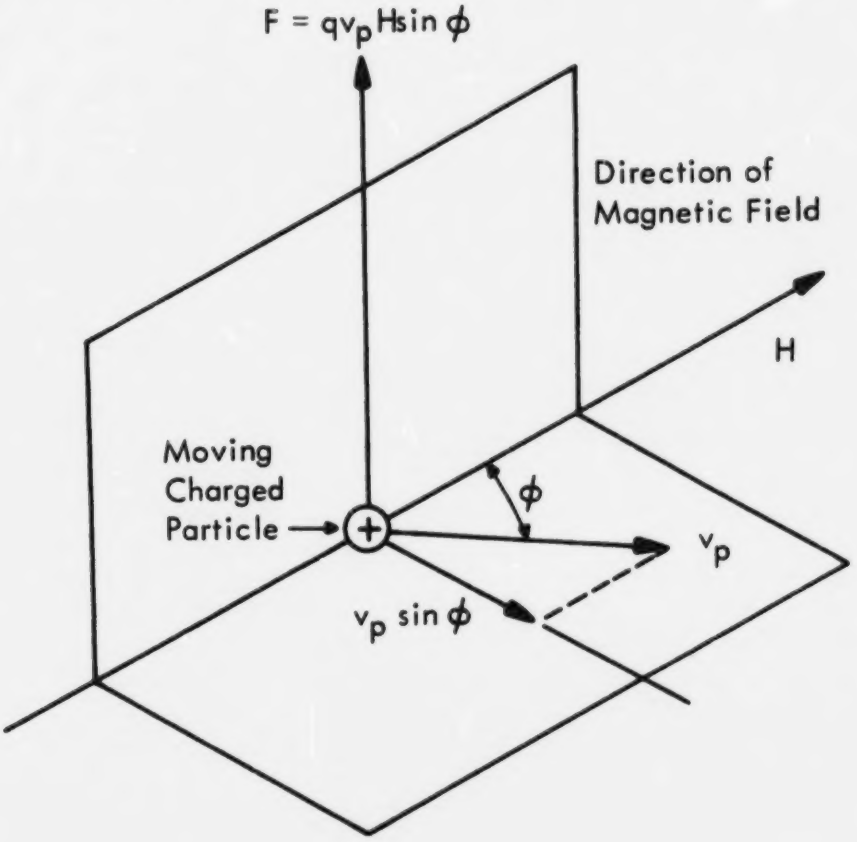

Figure 1. The magnetic force F acting on a charged particle.

$$Nqv_pH = \frac{3\pi\mu g d v_t}{C} \qquad (1)$$

where N = number of charges on particle

q = elementary charge

v_p = velocity of particle in field

H = magnetic field

μg = gas viscosity

d = particle diameter

v_t = terminal drift velocity of particle

C = Cunningham factor

The left-hand term in Eq. (1) represents the Lorentz force and the right term the gas resistance. Eq. (1) can be rearranged to yield the following expression for the terminal drift velocity:

$$v_t = \frac{Nqv_pHC}{3\pi\mu g\ d} \quad . \qquad (2)$$

Eq. (2) indicates that the terminal drift velocity varies directly with the number of charges on a particle, the particle velocity, and the magnetic field and inversely with the particle diameter. Since the drift velocity varies inversely with particle size, differentials in the drift velocity will exist in a polydisperse aerosol flowing through a magnetic field. The possibility of particle collision and agglomeration exists and the rate of either process will be dependent upon the magnitude of the differential in drift velocities and the residence time in the magnetic field as well as the fluid mechanics of a specific system.

Eq. (2) can be used to estimate values of the terminal drift velocity. Table 1 presents values of v_t calculated using typical values of the gas velocity encountered in gas cleaning operation. Gas velocities of 5 and 25 m/sec (1,000 and 5,000 fpm) were selected. Magnetic fields of 5×10^3, 10^4, and 10^5 gauss were used (a field of 10^4 gauss represents an efficient

Table 1. TERMINAL DRIFT VELOCITY OF PARTICLES IN A MAGNETIC FIELD

d (cm)	n	v_p (m/sec)	H (gauss)	v_t (cm/sec)
1×10^{-4}	1	5.1	5×10^3	2.4×10^{-7}
	100			2.4×10^{-5}
	1,000			2.4×10^{-4}
	1		10^4	4.8×10^{-7}
	100			4.8×10^{-5}
	1,000			4.8×10^{-4}
	1		10^5	4.8×10^{-6}
	100			4.8×10^{-4}
	1,000			4.8×10^{-3}
1×10^{-4}	1	25.5	5×10^3	1.2×10^{-6}
	100			1.2×10^{-4}
	1,000			1.2×10^{-3}
	1		10^4	2.4×10^{-6}
	100			2.4×10^{-4}
	1,000			2.4×10^{-3}
	1		10^5	2.4×10^{-5}
	100			2.4×10^{-3}
	1,000			2.4×10^{-2}
1×10^{-5}	1	5.1	5×10^3	2.4×10^{-6}
	100			2.4×10^{-4}
	1,000			2.4×10^{-3}
	1		10^4	4.8×10^{-6}
	100			4.8×10^{-4}
	1,000			4.8×10^{-3}
	1		10^5	4.8×10^{-5}
	100			4.8×10^{-3}
	1,000			4.8×10^{-2}

Table 1. (CONCLUDED)

d (cm)	n	v_p (m/sec)	H (gauss)	v_t (cm/sec)
1×10^{-5}	1	25.5	5×10^3	1.2×10^{-5}
	100			1.2×10^{-3}
	1,000			1.2×10^{-2}
	1		10^4	2.4×10^{-5}
	100			2.4×10^{-3}
	1,000			2.4×10^{-2}
	1		10^5	2.4×10^{-4}
	100			2.4×10^{-2}
	1,000			2.4×10^{-1}

Table 2. MAXIMUM PARTICLE CHARGE AS A FUNCTION OF PARTICLE SIZE (E_o = 2 x 10^6 volts/m)

Particle size d (micrometer)	Maximum number of charges, N_{max}
100	3.5 x 10^6
10	3.5 x 10^4
1	350
0.1	3.5

Inspection of Table 1 indicates that for the charge levels shown in Table 2, relative terminal drift velocities for fine particles of the order of 10^{-6} to 10^{-4} cm/sec result for reasonable values of v_p and H. Impaction mechanisms are precluded at such low relative velocities, but interception and diffusion processes might result in collision and agglomeration. Single particle target efficiencies of 0.2 to 0.5 for the combined effects of interception and diffusion appear likely and some collision and agglomeration may occur if the particles have sufficient residence time in the magnetic field to permit the particles to traverse the average distance between particles (i.e., the interparticle spacing distance).

The minimum residence time required for the particles to traverse the average distance between particles will depend upon the grain loading of the aerosol. For aerosols with a grain loading ranging between 2.29 and 22.9 g/m^3 (i.e., 1 and 10 grains/scf), interparticle spacing distances would be of the order of 10^{-3} cm. If the relative drift velocities are in the range of 10^{-4} to 10^{-6} cm/sec, residence times of 10 to 1,000 sec would be required for particles to traverse a distance of 10^{-3} cm. A residence time of 10 sec might be feasible in an industrial application, but 1,000 sec is clearly not. A residence time of 10 sec would require an effective magnetic field ranging from 45.72 to 228.6 m (i.e., 150 to 750 ft) in length (depending on gas velocity). Thus, the physical size of equipment required to treat gas streams of 2,831.7 m^3/min (i.e., 100,000 cfm) even if cylindrical, spherical, or U-shaped systems were designed, appears to be prohibitive.

permanent magnet). Examination of Table 1 shows that the terminal drift velocity is less than 0.01 cm/sec except at high particle velocities and magnetic fields indicating that magnetic fields alone do not offer any advantages as a mechanism for primary removal* of particles in a gas stream.

Since the force acting on the charged particle and the resultant drift velocity are dependent upon particle size, the relative motion of different-sized particles might be sufficient to bring them close enough to each other to undergo collision and agglomeration. A detailed calculation of the path of particles in a magnetic field and determination of whether or not collision and agglomeration would occur requires knowledge of the magnetic field distribution, gas flow pattern, and charge distribution on the particles.

A qualitative assessment of the likelihood of collision and agglomeration can be obtained by considering the magnitude of the charge on particles, the relative drift velocities between particles and the interaction of various particle collision mechanisms. At the outset it should be noted that if all the particles have a unipolar charge, collision is unlikely because particles of like charge will repel each other. If it is possible to achieve bipolar charging, then collision and agglomeration might occur. An estimate of the maximum number of charges that can reside on a particle can be obtained from various theoretical equations describing particle charging.[1/] If only field charging is considered, Eq. (3) can be used:

$$N_{max} = 4\pi\epsilon_o r_p^2 E_o \qquad (3)$$

where ϵ_o = permittivity of free space

r_p = particle radius

E_o = applied electric field

Table 2 presents a tabulation of maximum particle charge as a function of particle size for an electric field of 2×10^6 volts/m.

---

* i.e., a magnetic precipitator would not be feasible.

permanent magnet). Examination of Table 1 shows that the terminal drift velocity is less than 0.01 cm/sec except at high particle velocities and magnetic fields indicating that magnetic fields alone do not offer any advantages as a mechanism for primary removal* of particles in a gas stream.

Since the force acting on the charged particle and the resultant drift velocity are dependent upon particle size, the relative motion of different-sized particles might be sufficient to bring them close enough to each other to undergo collision and agglomeration. A detailed calculation of the path of particles in a magnetic field and determination of whether or not collision and agglomeration would occur requires knowledge of the magnetic field distribution, gas flow pattern, and charge distribution on the particles.

A qualitative assessment of the likelihood of collision and agglomeration can be obtained by considering the magnitude of the charge on particles, the relative drift velocities between particles and the interaction of various particle collision mechanisms. At the outset it should be noted that if all the particles have a unipolar charge, collision is unlikely because particles of like charge will repel each other. If it is possible to achieve bipolar charging, then collision and agglomeration might occur. An estimate of the maximum number of charges that can reside on a particle can be obtained from various theoretical equations describing particle charging.[1] If only field charging is considered, Eq. (3) can be used:

$$N_{max} = 4\pi\epsilon_o r_p^2 E_o \qquad (3)$$

where ϵ_o = permittivity of free space

r_p = particle radius

E_o = applied electric field

Table 2 presents a tabulation of maximum particle charge as a function of particle size for an electric field of 2×10^6 volts/m.

---

* i.e., a magnetic precipitator would not be feasible.

Table 2. MAXIMUM PARTICLE CHARGE AS A FUNCTION OF PARTICLE SIZE ($E_o = 2 \times 10^6$ volts/m)

Particle size d (micrometer)	Maximum number of charges, N_{max}
100	3.5×10^6
10	3.5×10^4
1	350
0.1	3.5

Inspection of Table 1 indicates that for the charge levels shown in Table 2, relative terminal drift velocities for fine particles of the order of 10^{-6} to 10^{-4} cm/sec result for reasonable values of v_p and H. Impaction mechanisms are precluded at such low relative velocities, but interception and diffusion processes might result in collision and agglomeration. Single particle target efficiencies of 0.2 to 0.5 for the combined effects of interception and diffusion appear likely and some collision and agglomeration may occur if the particles have sufficient residence time in the magnetic field to permit the particles to traverse the average distance between particles (i.e., the interparticle spacing distance).

The minimum residence time required for the particles to traverse the average distance between particles will depend upon the grain loading of the aerosol. For aerosols with a grain loading ranging between 2.29 and 22.9 g/m^3 (i.e., 1 and 10 grains/scf), interparticle spacing distances would be of the order of 10^{-3} cm. If the relative drift velocities are in the range of 10^{-4} to 10^{-6} cm/sec, residence times of 10 to 1,000 sec would be required for particles to traverse a distance of 10^{-3} cm. A residence time of 10 sec might be feasible in an industrial application, but 1,000 sec is clearly not. A residence time of 10 sec would require an effective magnetic field ranging from 45.72 to 228.6 m (i.e., 150 to 750 ft) in length (depending on gas velocity). Thus, the physical size of equipment required to treat gas streams of 2,831.7 m^3/min (i.e., 100,000 cfm) even if cylindrical, spherical, or U-shaped systems were designed, appears to be prohibitive.

Even if agglomeration could be achieved with acceptable equipment configurations, the use of magnetic fields to agglomerate charged particles appears to have dubious value. A particle charging system of some sophistication would be required* as a component of the system as well as a particle collection device downstream of the magnetic agglomeration chamber. Since the particles will probably have residual charge, an electrostatic precipitator would seem to be a logical choice for the collection device. If such is the case, it is difficult to justify placing a magnetic agglomeration system between what would basically be an electrostatic precipitator system.

The preceding qualitative analysis results in the conclusion that the use of magnetic fields to agglomerate charged particles is not attractive. Electrostatic agglomeration and subsequent collection in an ESP or direct collection in an ESP are more viable approaches.

MAGNETIC FIELDS AND UNCHARGED PARTICLES

Dipole forces, resulting from permanent dipole moments of aerosol particles or dipole moments generated in a magnetic field, may be sufficient to alter particle motion and cause collision and agglomeration. Very little attention has been directed to the utilization of dipole forces resulting from magnetic properties and fields for the agglomeration of particles. The limited work on the subject is reviewed in the next section.

Agglomeration of Particles with Permanent Dipole Moments

Aggregates of particles may form in the absence of an external magnetic field if the particles have permanent dipole moments. On approaching one another the dipoles orient themselves so that opposite dipoles attract. Theoretical studies of the coagulation of magnetic spherical dipoles have been conducted by Zebel.[2] Zebel employed a statistical mechanics approach in order to devise equations for the rate of coagulation of weak and strong dipoles. For weak dipoles, Zebel derived the following expression for the coagulation rate.

$$f = \frac{1}{1 - 0.0952\left(\frac{r_M}{r_{12}}\right)^6} \qquad (4)$$

* Bipolar charging would be necessary to avoid particle repulsion which would occur between unipolar charged particles.

where $f = \frac{\text{coagulation rate with dipoles}}{\text{coagulation rate in absence of dipoles}}$

$r_{12} = r_1 + r_2$ = sum of radii of particles 1 and 2

$r_M = \left(\frac{p_1 p_2}{kT}\right)^{1/3}$

p_1 = dipole moment of particle 1

p_2 = dipole moment of particle 2

k = Boltzmann constant

T = absolute temperature

The term r_M represents the distance of two dipoles, with moments = p_1 and p_2, at which their potential energy is equal to the thermal energy, kT. Thus, $r_M/r_{12} \gg 1$ means that at the contact distance of the particles their potential energy is large compared to the thermal energy; this is a strong interaction. Alternatively, $r_M/r_{12} \ll 1$ represents a very weak interaction. If $r_M \ll r_{12}$, Eq. (4) simplifies to:

$$f = 1 + 0.0952\left(\frac{r_M}{r_{12}}\right)^6 \qquad (5)$$

For the case of strong dipole interaction, the coagulation rate is given by Eq. (6):

$$f = \frac{r_M}{r_{12}} . \qquad (6)$$

Eq. (6) is generally applicable when $r_M > 1.4\, r_{12}$.

Evidence of the experimental verification of either Eqs. (4), (5), or (6) was not found in the literature. References 3 and 4 discuss the coagulation of particles which are permanent magnets. Iron and nickel smokes, having particles which are permanent magnets, were generated by heating the vapors of the carbonyls in the absence of oxygen. Below the Curie point (360°C for nickel and 770°C for iron) the smokes coagulate

to thread-like aggregates but above it rounded aggregates or very short chains are formed. Thread aggregates orient themselves in a magnetic field and turn through 180 degrees when the field is reversed, thus showing that the orientation is not due to induction but due to permanent magnetism of the particles. How the magnetism originates is not known. Smokes of iron oxide crystals have similar properties but particles of amorphous iron oxide are not ferromagnetic and do not give linear aggregates without an external field.

It should be noted that very few particles possess permanent magnetic properties (only iron, nickel, and cobalt and some alloys are ferromagnetic). Because only a few particles have permanent magnetic properties, limited opportunities will exist to exploit particle agglomeration by this technique. Agglomeration by this mechanism will occur naturally whenever it is possible and efforts to enhance the process appear to have little merit.

Dipole Moments Generated in a Magnetic Field

Dipole moments can be generated when uncharged particles are placed in a magnetic field. If a homogeneous magnetic field of strength H is used, it will polarize spherical aerosol particles with radius r_p to dipoles having moments:

$$m = \frac{\mu - 1}{\mu + 2} r_p^3 H \tag{7}$$

where μ = magnetic permeability of particle.

By making simplifying assumptions regarding particle motion and assuming that $\frac{\mu - 1}{\mu + 2}$ is equal to unity (i.e., ferromagnetic material), Fuchs[5] has shown that a distinct increase occurs in the factor f (see Eq. (4)) when $r_M/r_p^3 > 20$.

Under the above conditions (i.e., strong attraction), the ratio of the rate of coagulation with and without dipole forces is:

$$f = \frac{H^2 r_p^3}{12kT} \tag{8}$$

From the preceding it is readily apparent that acceleration of agglomeration of fine particles by induced magnetic dipoles will only occur in strong fields and for ferromagnetic materials.

If a nonhomogeneous magnetic field (Figure 2) is used, a force will act on the particles which might result in deflection of particles with resultant collision and agglomeration. For this case, Zebel presents the following equation for the force:[6]

$$K = \alpha/2 \text{ grad } H^2 \tag{9}$$

where $\alpha = \frac{\mu - 1}{\mu + 2} r_p^3$

μ = magnetic permeability of particle

r_p = particle radius

Detailed calculations of the path of particles and determination of whether or not they will collide and agglomerate require a knowledge of the magnetic field distribution, particle size distribution, particle grain loadings, magnetic permeabilities of particles, and the gas flow pattern. As was noted previously, only few materials possess high magnetic permeabilities and it is likely that only ferromagnetic materials would show any significant agglomeration.

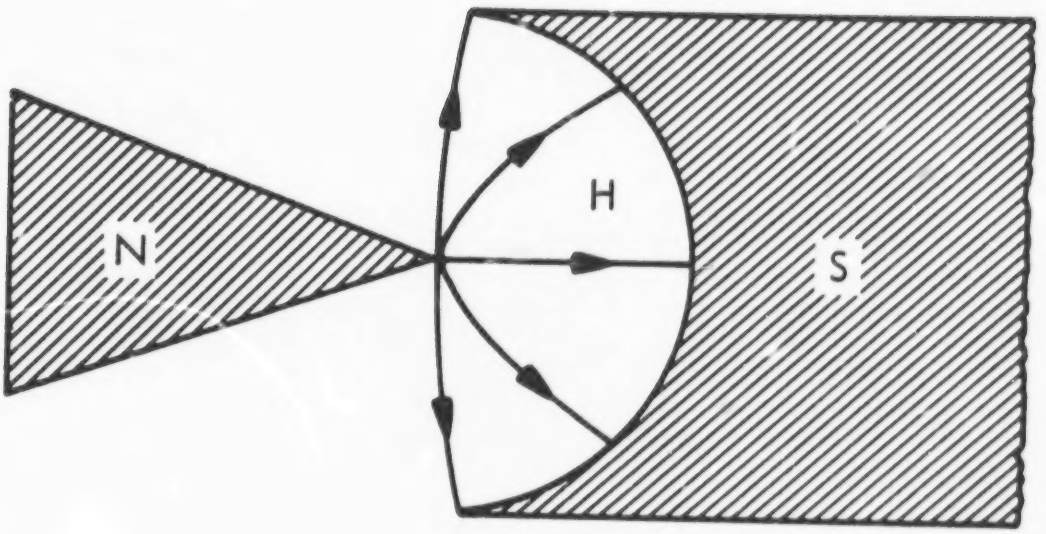

Figure 2. Arrangement to generate a strongly nonhomogeneous magnetic field H, which can be used to separate ferromagnetic particles (N and S designate the north and south pole, respectively).

SECTION III

MAGNETIC SEPARATION

Magnetic separation is an old technique whose use has been restricted in the past to the separation of strongly magnetic materials like iron and magnetite. A good example of this type of separator is the conventional drum-type magnetic separator.[7] Currently, magnetic separation of weakly magnetic materials (weak paramagnetic materials) is made possible with the aid of high magnetic field gradients. One such device is the "high gradient magnetic separator" (HGMS). Since particulates emitted from most industrial sources are not ferromagnetic, this discussion will be limited to the more widely applicable HGMS.

The literature contains several articles on HGMS and its operating principle and potential application areas.[7-12] The application areas discussed include mineral beneficiation (of taconite iron ores), coal desulfurization, and wastewater treatment. Unfortunately, none of the papers discuss the potential use of HGMS in controlling particulates in industrial gas streams. However, the principle and operation of the device are independent of the application area. A brief discussion of the HGMS concept is presented next.

OPERATION OF A HGMS

Figure 3 is a schematic of a Kolm type HGMS.[7,9] A magnet designed to produce a strong variable field in the canister volume is used. This volume is packed with a matrix of filamentary, ferromagnetic material. These filaments produce large surface areas of high magnetic gradients along their edges and they resist compression and clumping in the applied magnetic field. The filaments are chosen to match the size of the particles to be removed in order to optimize the magnetic forces. The feed in a fluid (usually water) slurry, is passed down through the canister.[7] The fluid and nonmagnetic particles pass easily through the relatively open structure of the matrix. The trapped magnetic particles are easily washed out when the applied field is reduced to zero.[7]

PRINCIPLE OF A HGMS

The principle of operation of a HGMS is reviewed in detail in Reference 7. A brief summary of the review highlighting those aspects which are critical to particulate collection in industrial gas streams is presented in the following paragraphs.

A simple expression for the magnetic force acting on a particle is (in the x component):

$$F_x = \int (M_p - M_m) \frac{dH}{dx} \cdot dV \qquad (10)$$

In Eq. (10), M_p and M_m are the magnetization of the particle and medium, respectively; V is the volume of the particle and dH/dx the magnetic field gradient. According to Eq. (10), for a specific particle size (volume) any increase in magnetization or the field gradient should improve the magnetic force. The magnetization (M) itself is a function of the susceptibility* and the magnetic field strength as shown in Eq. (11).

$$M = \chi B \qquad (11)$$

Substitution of Eq. (11) in Eq. (10) and integration yields:

$$F_x = (\chi_p - \chi_m) B(b) \cdot \frac{dH(b)}{dx} \cdot V \qquad (12)$$

where b is a point within the particle having volume V (see Figure 4).

In Eq. (12), χ_p, χ_m and V are intrinsic properties. The only parameters that can be varied to enhance F_x are the magnetic field strength $B(b)$ and the field gradient $dH(b)/dx$. Even with a constant field strength, the magnetic force could be improved by altering the field gradient. For an applied field H_o less than bulk satuation field H_s, along the axis, the magnetic field gradient at the particle is given:[7]

$$\frac{dH}{dx} = -2H_o \frac{a^2}{b^3}$$

Therefore, there is a certain filament radius (a) which will maximize the magnetic force on a given particle. Oberteuffer[7] reports that this

* Magnetic susceptibility, $\chi = \mu/\mu o - 1$ where "μ" is the magnetic permeability of the material (particle) and "μo" is the magnetic permeability of vacuum.

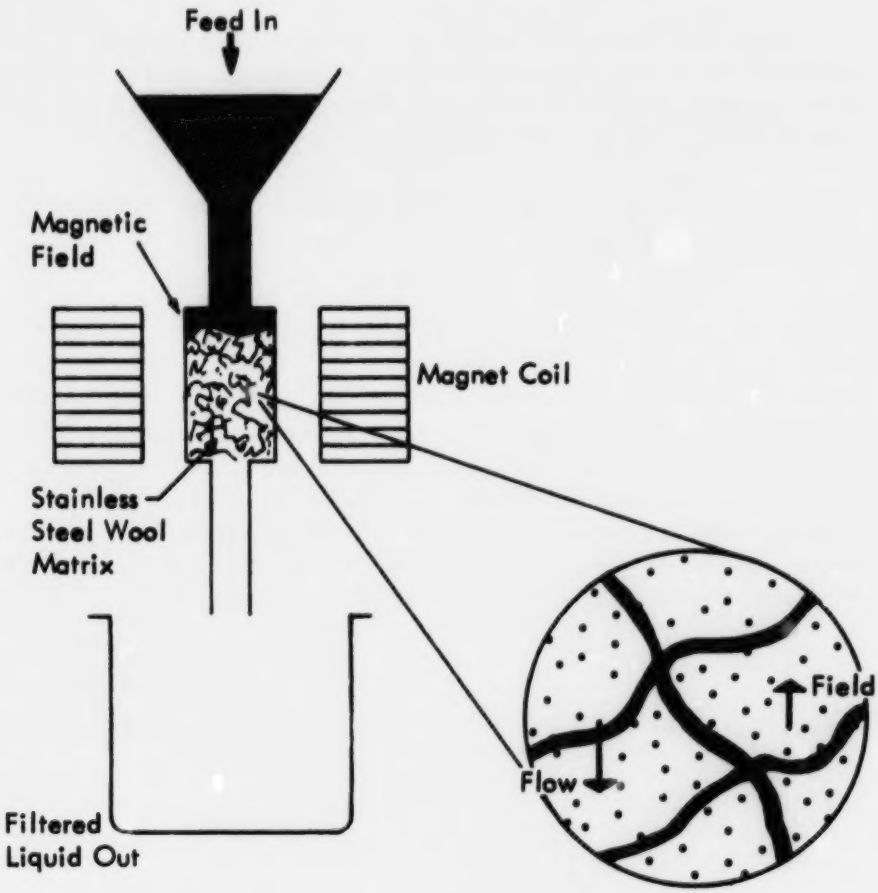

Figure 3. Schematic representation of Kolm type high gradient magnetic separator.[3,9]

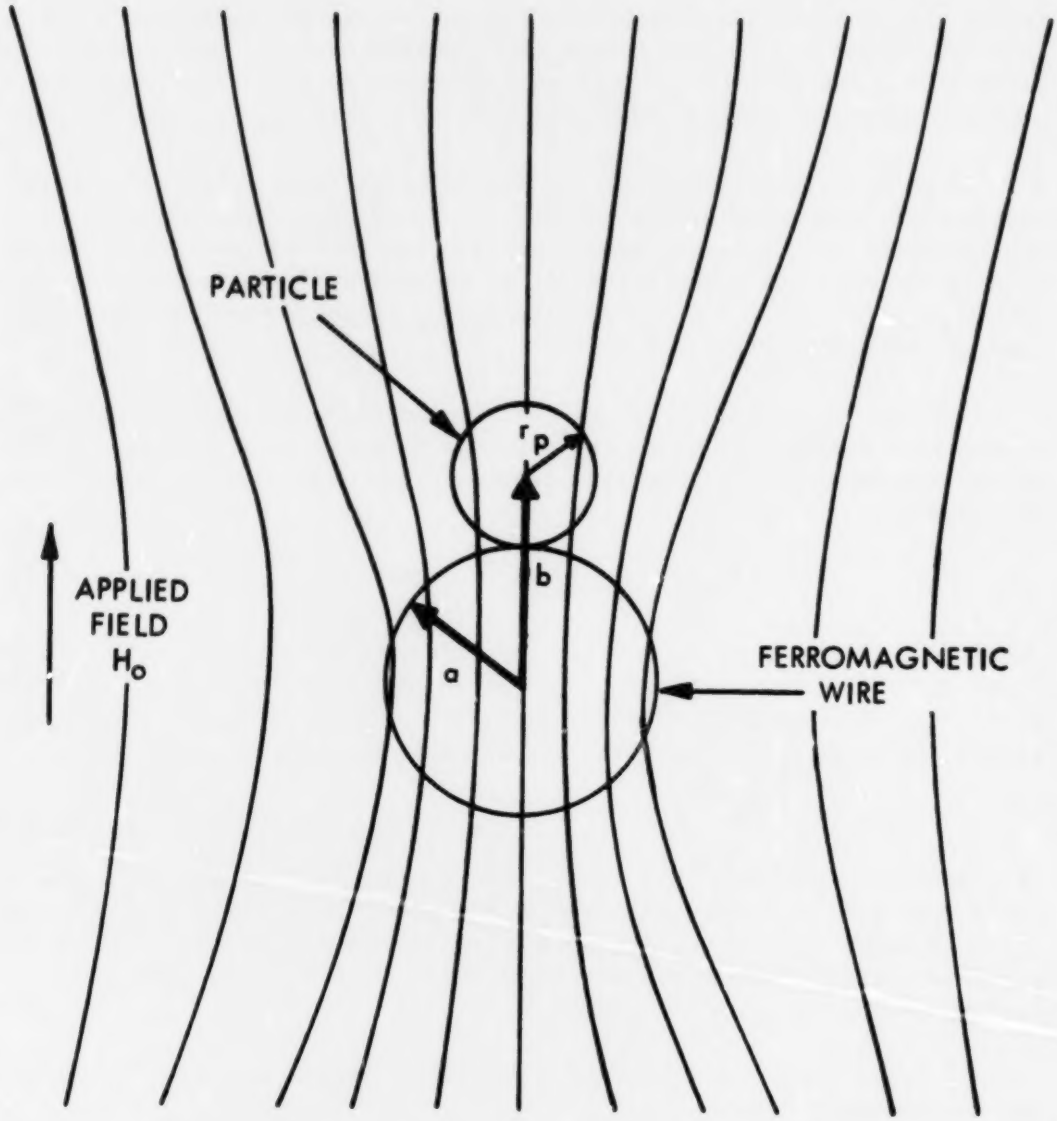

Figure 4. Cross section of spherical particle, radius r_p attached to ferromagnetic wire, radius a, magnetized by uniform magnetic field H_o.

radius should be of the same order of magnitude as the particle radius and, to be more precise, is three times the particle radius. One apparent disadvantage is the fact that a high efficiency of magnetic separation can be achieved only for certain sized particles in a polydispersed gas stream.

It is also to be noted that if the magnetic force falls off significantly over a distance of one particle diameter, each trapping site in the separator will have a capacity of approximately one particle. Therefore to increase the number of sites in separators it is desirable to use fibers or wires since the number of trapping sites is approximately the same as the volume of the fibers.[7]

Another consideration in the HGMS is the need to determine the range of particle radius over which the magnetic force is greater than the competing forces of gravity and hydrodynamic drag. The gravitational force is given by:

$$F_g = \frac{4}{3} \pi r_p^3 (\rho_p - \rho_f) g \qquad (13)$$

where r_p is the particle radius, ρ_p and ρ_f the densities of the particle and medium, respectively, and g the local accleration of gravity. Since F_g is a function of r_p^3, the gravitational force will be significant for large particles. The hydrodynamic drag force given by:

$$F_d = 6\pi\eta r_p v \qquad (14)$$

is significant for small particles. In Eq. (14), η is the viscosity of the medium and v is the velocity of the particle relative to the stream. Figure 5 shows the magnetic and competing forces versus particle size for a gradient-matched separator where the filament size is matched with the size of the particle to be trapped.[7]

It can be observed from Figure 5 that the magnetic force (F_m) exceeds the hydrodynamic drag force (F_d) in a water slurry, only for particles of size greater than 1 to 10 μm. This result means that for CuO particles < 1 μm in size the hydrodynamic drag force predominates in a water slurry system and capture by magnetic forces is ruled out. We have extended this analysis to an air system to determine the applicability of magnetics in gas cleaning which is of greater concern to us. The F_d lines for air at two different velocities have been calculated and included in Figure 5. It is interesting to note that in an air system the magnetic force (F_m) dominates the drag force (F_d) even for particles < 0.1 μm at a velocity of 5 cm/sec. Higher particle velocities shift the effectiveness of the magnetic force toward larger particles. For an air velocity of 50 cm/sec, which is close to the typical value for an industrial gas system, the magnetic force is effective down to about 0.3 μm.

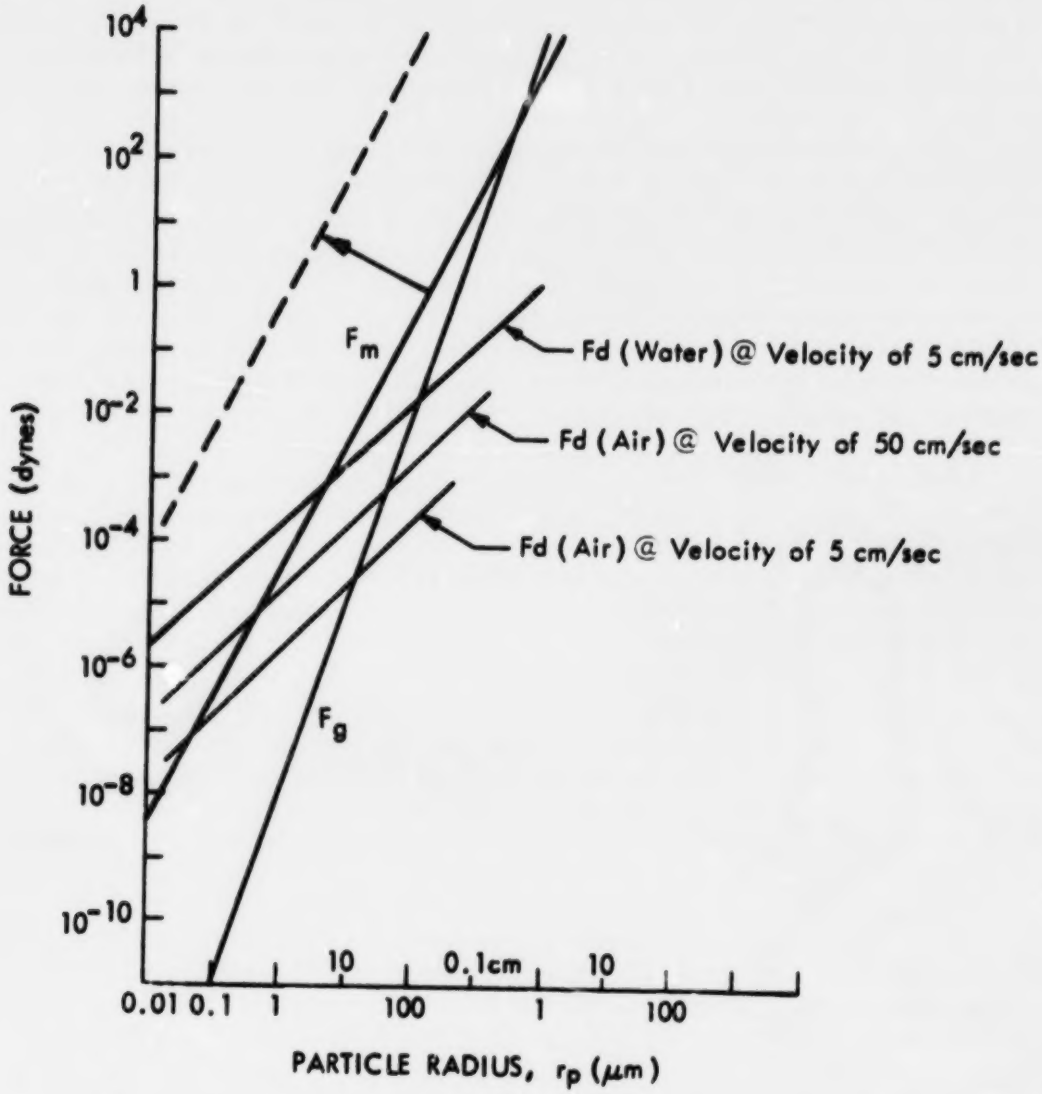

Figure 5. Log-log plot of magnetic (F_m) and competing gravitational (F_g) and drag forces (F_d) versus particle size r_p for magnetized wire whose size is matched to that of particle to be trapped. Computed for CuO particle attracted by ferromagnetic wire of radius $3r_p$ magnetized by 10 KOe field strength and acted upon by slurry with velocity of 5 cm/sec.[7]

If, instead of CuO particles, one uses Fe_3O_4 which has a much higher magnetic permeability, then the line depicting magnetic force (F_m) in Figure 5 would move to the left. This shift is shown by the dashed line. The shift in the line caused by particles of high magnetic permeability would thus enable the capture of particles well into the submicron region.

For a given range of magnetization, the range of particles separable in a HGMS and in an "ideal" separator have also been reported for a water slurry system.[2/] The "ideal" separator has a wire (filament) radius approximating the particle size (i.e., it is gradient-matched) and is assumed to operate at a magnetic field intensity of 10 KOe* and a water slurry velocity of 5 cm/sec. The lower and upper limits of particles that can be captured in such a device have been calculated by equating the competing forces, i.e., magnetic force (F_m) with the drag force (F_d) and the magnetic force (F_m) with the gravitational force (F_g), respectively.

For an air system, however, the gravitational force can aid collection if the flow of air to be scrubbed is upward. In such a case the only limiting factor is F_d, the drag force. We have used this approach to determine the lower limit of particle size that can be captured in a gradient-matched system with a magnetic field of 10^4 gauss for materials with different magnetizations when drag is the only competing force. The results of the calculations are shown in Figure 6 for a gas velocity of 5 cm/sec. It can be observed from Figure 6 that for a material with a magnetization of 1 amp/m, the smallest particle that can be captured is 4 μm. For a material of magnetization 10 amp/m the smallest particle captured would be 0.4 μm. An increase in magnetic field or decrease in flow velocity will shift the curve to the left thus increasing the range of separable particles.

From an analysis of Figures 5 and 6 and the concepts underlying high gradient magnetic separation, we have summarized the critical parameters to be considered in using a HGMS for particulate control in gas streams. These may be listed as:

* Size distribution of particles to be removed and grain loading of gas stream.

* Range of magnetic permeability of the particles for gas stream temperatures.

---

* A field intensity of 10 KOe corresponds to a field of 10,000 gauss when the permeability of the material is 1 and to 100 gauss when it is 0.01. The magnetic field of the earth is about 0.5 gauss, a typical small permanent magnet has a field of about 100 gauss and a large electromagnet about 20,000 gauss.

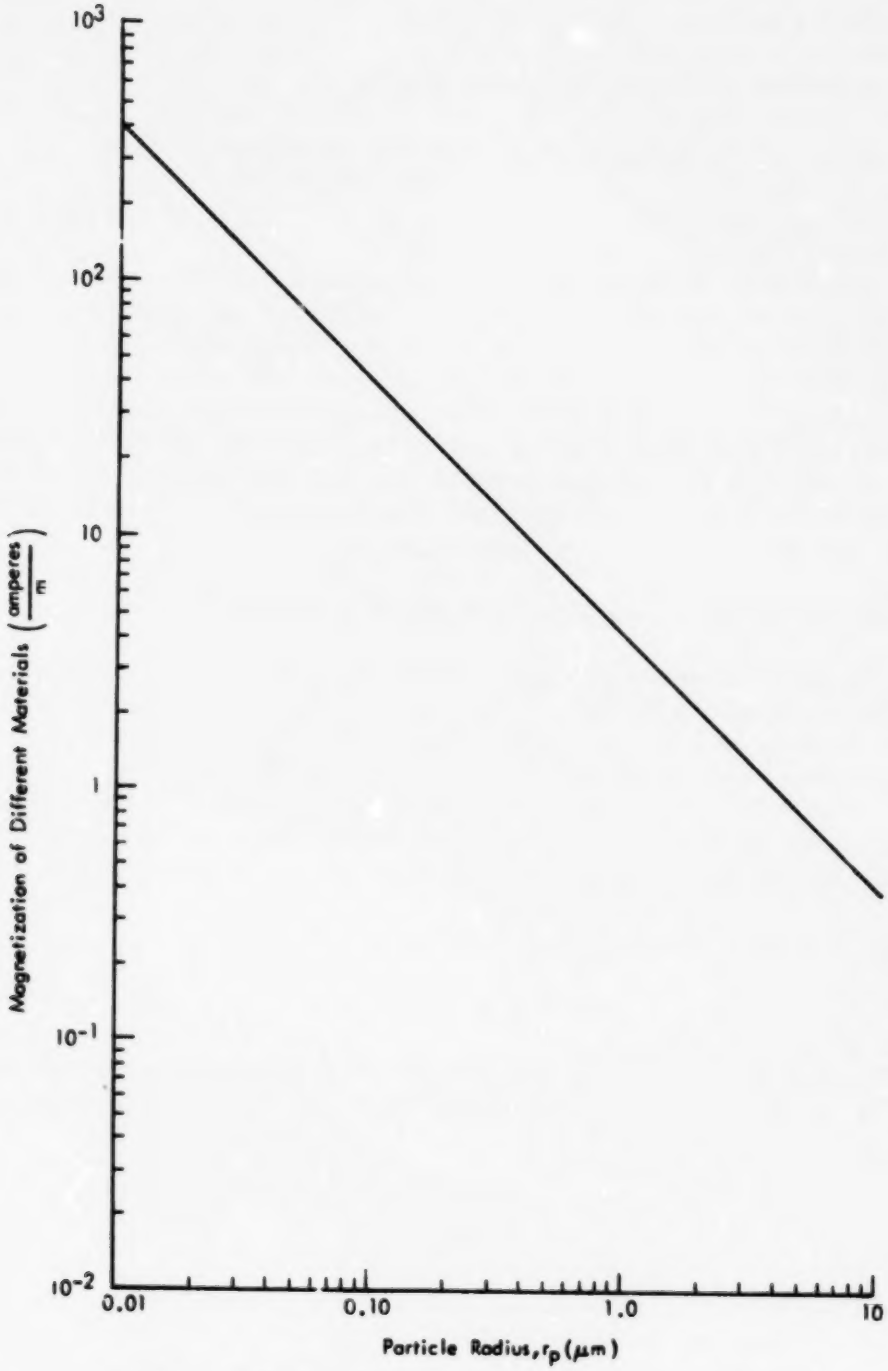

Figure 6. Log-log plot of magnetization versus particle radii

* Gas stream flow rates/velocities.

* Gas stream viscosity and density.

* Selection of appropriate wire diameter.

* Selection and generation of required field intensities.

LABORATORY STUDY OF HGMS

Unfortunately, there is no direct experience available in the use of such a system for particulate control in industrial gas streams. Apparently, the only study that is being conducted to determine the use of a HGMS in scrubbing fine particles in gas streams is a laboratory study at Research Triangle Institute (RTI) under EPA sponsorship. The gas stream under test at RTI is dust from the basic oxygen furnace in prefiltered room air. Efficiencies of the order of 90% for particulates > 0.3 μm have been observed with an optical particle counter in the preliminary experiments[13] and no other data are available.

COMPARISON OF MAGNETIC FORCE WITH CONVENTIONAL MECHANISMS

It is interesting to compare particulate capture due to conventional mechanisms such as impaction, interception, and diffusion with that due to magnetic forces. Let us take a case where there is no magnetic force acting on the particle and the wires act as targets for interception, inertial impaction, and diffusion of the particles at a gas velocity of 5 cm/sec. Let us also assume that the wire diameter is three times the particle diameter in order to conform to a gradient-matched magnetic separator.

The interception efficiency is given by:[14]

$$\eta_c = 1 + R - \frac{1}{(1 + R)} \tag{15}$$

where R = ratio of particle diameter to that of the intercepting body (in our case, R = 0.33). The inertial impaction parameter is given by:[14]

$$\psi = \frac{C\, \rho_p\, v\, D_p^2}{18 \mu g D_b 10^4} \tag{16}$$

where C = empirical correction factor for resistance of gas to movement of small particles

= 1 (assumed for 2 μm particle)

Reproduced from best available copy.

ρ_p = particle density in g/cc = 2.8 g/cc (equivalent to iron foundry particles)

v = velocity of particle in cm/sec

= velocity of gas, = 5 cm/sec

D_p = particle size in μm

= 2 μm

μ_g = viscosity of gas in poises 1.8×10^{-4} poises (for air)

D_b = diameter of wire in μm

= 6 μm

The diffusional efficiency is:[14]

$$\eta_D = \frac{}{Pe}\left(\frac{1}{} + 0.55\ Re^{1/2}\ Sc^{1/3}\right) \qquad (17)$$

where Pe = peclet number = Re Sc = $\frac{D_p v}{\mathcal{D}}$

Re = Reynolds number = $\frac{D_p v \rho}{\mu_g}$

Sc = Schmidt number = $\frac{\mu_g}{\rho \mathcal{D}}$

In Eq. (17), D_p is the particle diameter (2 μm), v is the particle velocity (5 cm/sec), ρ_p the density of the particle (2.8 g/cc), μ_g viscosity of air and $\mathcal{D}$ the diffusivity of the particle (assumed to be 2.7×10^{-7} cm^2/sec).[14]

For the conditions indicated above the interception efficiency is calculated to be 587 and the impaction parameter is 0.29. At the latter value the impaction efficiency is zero.[14] The diffusional efficiency is · 12.[14] If, under the above conditions, magnetic forces can help capture all of the 2-μm particles, then systems utilizing magnetic forces could be rated as being superior to those devices which only make use of the conventional mechanisms. Inspection of Figure 5 shows that at a gas (air) velocity of 5 cm/sec the magnetic force is effective up to about 0.05 μm. One obvious route to enhance the performance of a magnetic separator is to use magnetic seeding of the gas stream to be scrubbed with high permeability particulates. However, on an industrial basis this approach does not appear viable.

SECTION IV

CONCLUSIONS

The use of magnetic fields to agglomerate either charged or uncharged particles is of no apparent utility in industrial gas cleaning applications. In the case of charged particles, residence times clearly in excess of those tolerable in industrial situations would be required to achieve any appreciable agglomeration. Only ferromagnetic materials could be agglomerated by dipole forces and the paucity of ferromagnetic materials in most industrial emissions makes that approach nearly useless. Also, it is quite likely that unacceptable residence times would be required to effectively utilize dipole forces.

Direct magnetic separation on the other hand appears to be of potential value for fine particulate control in industrial gas streams. However, it has never been used for this application and only a laboratory scale study is currently under way to test the HGMS for particulate control in specific gas streams (i.e., streams containing high permeability particles). A detailed review of the results of the present study including aspects such as fractional efficiency versus magnetic permeability of the particle, particulate entrainment, wire (filament) diameter, and pressure drop would be critical prior to further investigation. Also, the economic aspects of the device, particularly the energy required to generate large magnetic gradients in field size units, should be evaluated in the absence of superconducting magnets. Thus, it can only be said that the HGMS is attractive, in principle, for particulate control in gas streams and warrants further investigation to assess its actual utility.

REFEPENCES

1. Robinson, M., Electrostatic Precipitation, published in Air Pollution Control, Part I, Wiley-Interscience (1971).

2. Zebel, G., Staub, 19(11), 381 (1959).

3. Berscher, D., and A. Winkel, A. Phys. Chem., 176A, 1 (1936).

4. Berscher, D., and A. Winkel, Naturwiss., 25, 420 (1937).

5. Fuchs, N. A., The Mechanics of Aerosols, Pergamon Press, New York (1964).

6. Zebel, G., Staub (English Traslation), 28(7), 1 (1968).

7. Oberteuffer, J. A., IEEE Transactions on Magnetics, MAG-10(2), 223, June 1974.

8. Kolm, H., J. Oberteuffer, and D. Kelland, Scientific American, p. 47, November 1975.

9. Oberteuffer, J. A., IEEE Transactions on Magnetics, MAG-9(3), 303, September 1973.

10. Kelland, D. R., IEEE Transactions on Magnetics, MAG-9(3), 307, September 1973.

11. Trindade, S. C., and H. H. Kolm, IEEE Transactions on Magnetics, MAG-9(3), 310, September 1973.

12. De Latour, C., IEEE Transactions on Magnetics, MAG-9(3), 314, September 1973.

13. Private communication with Mr. Charles Gooding, Research Triangle Institute, North Carolina, February 9, 1976.

14. Strauss, W., Industrial Gas Cleaning, Pergamon Press, New York (1966).